

Nuclear modification of charged hadron production at LHC

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Abstract. We analyze the recent results for suppressed production of charged hadrons for Pb+Pb collisions at the centre of mass energy of 2.76 TeV/nucleon. We closely follow the treatment used recently by us where partons lose energy due to radiation of gluons following multiple scatterings while traversing the quark gluon plasma, before fragmenting into hadrons at 200 GeV/nucleon. We obtain an empirical value for the momentum transport coefficient (\hat{q}) and provide predictions for azimuthal anisotropy of hadron momenta for non-central collisions.

PACS numbers: 12.38.Mh, 12.38.-t, 25.75.Cj, 25.75.Dw

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The degradation of energy of high momentum partons or *jets* inside the hot QCD medium manifests itself as a depletion of particles having large transverse momenta (p_T) in nucleus-nucleus (AA) collisions at relativistic energies, when compared with the corresponding results for proton-proton (pp) collisions. This phenomenon, often referred as *jet quenching* [1], is described by the nuclear modification factor R_{AA} :

$$R_{AA}^h(p_T, b) = \frac{d^2 N_{AA}(b)/dp_T dy}{T_{AA}(b)(d^2 \sigma_{NN}/dp_T dy)}, \quad (1)$$

where the numerator gives the inclusive yield of hadrons in AA collisions for the impact parameter b and the denominator gives the inclusive cross-section of hadron production in pp collisions scaled with the nuclear overlap function $T_{AA}(b)$.

According to perturbative QCD, the production cross-section of a hadron h having a large transverse momentum in pp collisions is written schematically as:

$$\frac{d\sigma^{AB \rightarrow h}}{dp_T dy} \sim f_i^A(x_1, \mu_F^2) \otimes f_j^B(x_2, \mu_F^2) \otimes \sigma^{ij \rightarrow k}(x_1, x_2, \mu_R^2) \otimes D_{k \rightarrow h}^0(z, \mu_f^2),$$

where $f_i^A(x_1, \mu_F^2)$ is the parton distribution function of the i -th parton, carrying a momentum fraction x_1 from the hadron A and similarly for $f_j^B(x_2, \mu_F^2)$. The parton-parton cross-section $\sigma^{ij \rightarrow k}(x_1, x_2, \mu_R^2)$, includes all the leading order $\mathcal{O}(\alpha_s^2)$ and next-to-leading $\mathcal{O}(\alpha_s^3)$ processes. $D_{k \rightarrow h}^0(z, \mu_f^2)$ is the vacuum fragmentation probability of the parton k into hadron h at the momentum fraction $z = p_h/p_k$.

Continuing our earlier study of jet quenching [2] at top Relativistic Heavy Ion Collider energy (RHIC) (200 GeV/nucleon), we analyse the recent results obtained at the Large Hadron Collider (LHC) at the center of mass energy of 2.76 TeV/nucleon. As a first step we show our results for the transverse momentum cross-sections of charged hadrons for pp collisions at 2.76 TeV (Fig 1). We have used the same set of structure functions (*CTEQ4M*) [3] and fragmentation functions (*BKK*) [4] as before. We give results for the factorization (μ_F), renormalization (μ_R) and fragmentation (μ_f) scales as equal to Q , with $Q = 0.5p_T$, p_T , and $2.0p_T$ and use NLO pQCD [5]. The "data" are the estimates used by the CMS Collaboration in these studies [6]. Buoyed by this success we have used the scale $Q = p_T$ for the subsequent studies.

Next we have calculated the inclusive production of charged hadrons for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, accounting for the multiple scattering and energy loss of partons inside the medium and nuclear shadowing. We have used the EKS98 parameterization [7] of nuclear shadowing.

We use the Wang-Huang-Sarcevic model [8] of multiple scattering as before and assume that the probability that a parton traversing a distance L undergoes n multiple scatterings is given by:

$$P(n, L) = \frac{(L/\lambda)^n}{n!} e^{-L/\lambda}, \quad (2)$$

where λ is the mean free path of the parton. We have kept it fixed as 1 fm for both quarks and gluons. The formalism of parton energy loss is adopted from Baier *et. al.* [9] where the light partons are assumed to lose energy only through gluon bremsstrahlung.

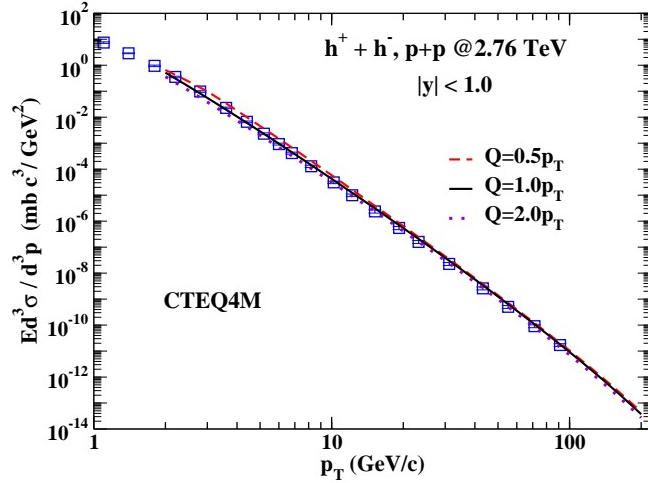


Figure 1. (Color online) The differential production cross-section of charged hadrons for p+p collisions at 2.76 TeV calculated using NLO pQCD and compared with the estimates by CMS Collaboration [6].

The formation time of a radiated gluon of energy ω and transverse momentum k_T is defined as $t_{\text{form}} \approx \omega/k_T^2$. Depending on the formation time of the radiated gluon, we consider three different regimes of energy loss (see [9, 2] for details). When the formation time is less than mean free path ($t_{\text{form}} < \lambda$) of the parton, we are in the Bethe-Heitler (BH) regime of incoherent radiation. The energy loss per unit length in this regime is proportional to the energy of the parton (E):

$$-\frac{dE}{dx} \approx \frac{\alpha_s}{\pi} N_c \frac{1}{\lambda} E , \quad (3)$$

where $N_c = 3$. If the formation time is greater than mean free path but less than the path length L ($\lambda < t_{\text{form}} < L$), we have a coherent emission of gluon radiation over $N_{\text{coh}} (= (\omega/\lambda k_T^2)^{1/2})$ number of scattering centers. This is called as LPM regime and the energy loss per unit length becomes:

$$-\frac{dE}{dx} \approx \frac{\alpha_s}{\pi} \frac{N_c}{\lambda} \sqrt{\lambda k_T^2 E} . \quad (4)$$

Finally, if the formation time is greater than the path length L ($t_{\text{form}} > L$), we are in the complete coherence regime of energy loss where the whole medium acts as one coherent source of radiation. The energy loss per unit length in this regime becomes proportional to the path length.

$$-\frac{dE}{dx} \approx \frac{\alpha_s}{\pi} N_c \frac{\langle k_T^2 \rangle}{\lambda} L . \quad (5)$$

A more careful calculation for Eq. 5 yields:

$$-\frac{dE}{dx} = \frac{\alpha_s}{4} N_c \hat{q} L , \quad (6)$$

where \hat{q} is the momentum transport coefficient. It may be noted that the coherence (or the absence of it) among the radiated gluons results in a varying dependence of the

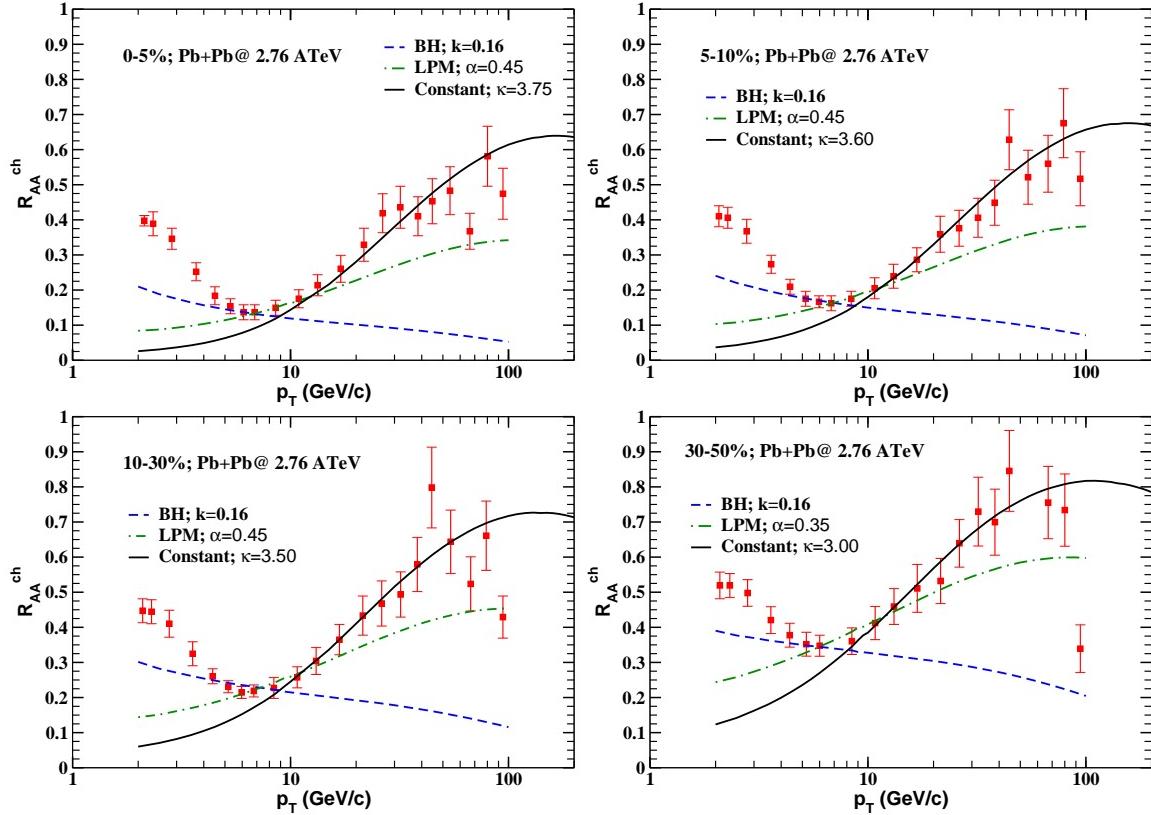


Figure 2. (Color online) Nuclear modification factor of charged hadron production calculated for Pb+Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV, in the BH, LPM, and complete coherence regimes of energy loss and compared with the measurements by the CMS collaboration [10]. Note that k is dimensionless, α is in the unit of $\text{GeV}^{1/2}$ and κ has the unit of GeV.

energy loss per unit length on the energy (E) of the parton. We shall use this expression to estimate \hat{q} , as for these cases, the energy loss per unit length is independent of energy of the parton and it is convenient to compare our results for different centre of mass energies of the collision and different centralities. The energy loss per collision, $\varepsilon = \lambda dE/dx$, is introduced as a free parameter in these studies. We write $\varepsilon=kE$, $\sqrt{(\alpha E)}$, or κ for BH, LPM, and complete coherence regimes of energy loss respectively, where k is dimensionless, α is in the unit of $\text{GeV}^{1/2}$ and κ has the unit of GeV. The parameters k , α , κ are varied to get an accurate description of the nuclear modification factor of charged hadrons (R_{AA}^{ch}) at different centralities of collisions. The average path length $\langle L \rangle$ of the parton inside the medium for a given centrality is calculated using optical glauber model (see Ref. [2]).

The energy loss of parton affects the particle production through the modification of vacuum fragmentation function. Following Ref. [8], we write the modified fragmentation function as:

$$zD_{k \rightarrow h}(z, \langle L \rangle, Q^2) = \frac{1}{C_N} \sum_{n=0}^N P(n, \langle L \rangle) \times \left[z_n D_{k \rightarrow h}^0(z_n, Q^2) + \sum_{m=1}^n z_m D_{g \rightarrow h}^0(z_m, Q^2) \right] ,$$

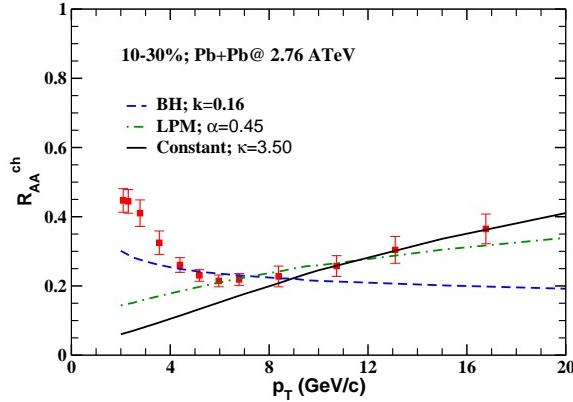


Figure 3. (Color online) The charged hadron nuclear modification factor for the centrality class 10-30% is plotted on a linear scale for a smaller p_T range. Note that k is dimensionless, α is in the unit of $\text{GeV}^{1/2}$ and κ has the unit of GeV .

where $z_n = zE_T/(E_T - \sum_{i=0}^n \varepsilon^i)$, $z_m = zE_T/\varepsilon_m$. The first term represents the hadronic contribution of a leading parton with a reduced energy ($E_T - \sum_{i=0}^n \varepsilon^i$) and the second term represents the hadronic contribution of the emitted gluons, each having energy ε_m . $C_N = \sum_{n=0}^N P(n, \langle L \rangle)$ and N is the maximum number of collisions suffered by the parton, equals to E_T/ε . We add that this treatment explicitly accounts for the fluctuations in the number of collisions, the parton may undergo in covering a distance L .

The suppressed production of charged hadrons for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is calculated for four centralities of collision, namely, 0-5%, 5-10%, 10-30%, 30-50% for BH, LPM and complete coherence regimes of energy loss (see Ref. [11] for several other analyses at this center of mass energy). As mentioned earlier, we have tuned the parameters k , α , κ systematically to have a good agreement with the recent measurement of R_{AA}^{ch} from CMS collaboration [10]. The results are shown in Fig. 2.

We find the BH mechanism works well over a small window of p_T , 5–8 GeV/c . Of course, at lower p_T the parton recombination dominates over fragmentation process for particle production at RHIC energies [12]. In addition the hydrodynamic flow of the system should affect the hadron spectra for p_T up to 5 GeV/c . As we go towards higher p_T , the BH contribution to nuclear modification gradually drops and the LPM mechanism is seen to explain the data for the p_T range $\sim (6\text{--}15) \text{ GeV}/c$ and even beyond for far-central collisions (30-50%).

The change in curvature of R_{AA}^{ch} near 10 GeV/c is correctly followed by complete coherence regime of energy loss. It gives a good description of data over a broad region of p_T ; $10 \text{ GeV}/c < p_T < 100 \text{ GeV}/c$. Further, the dominance of coherent regime of energy loss over the incoherent regime for $p_T > (6\text{--}8) \text{ GeV}/c$ can be seen from Fig. 3, where we replot our results in the p_T range $(0\text{--}20) \text{ GeV}/c$ on a linear scale. Some recent works of jet-quenching [13, 14] have also demonstrated this changing mechanism of parton energy loss with p_T for the central collisions.

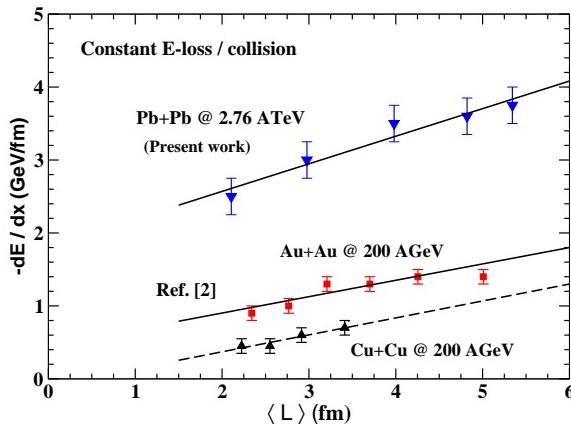


Figure 4. (Color online) dE/dx vs average path length, $\langle L \rangle$ of the parton, for Pb+Pb collisions at LHC. The results for Au+Au and Cu+Cu collisions are taken from ref [2]. The corresponding partons have $p_T > 8$ GeV/ c for RHIC energies and $> 10\text{--}12$ GeV/ c for LHC energies.

We note that while the parameter κ varies monotonically with the centrality of collision (i.e. average path length $\langle L \rangle$), the parameters k and α are seen to vary only marginally with $\langle L \rangle$.

It is interesting to study the variation of dE/dx with path length for complete coherence regime, which is seen to work well in the range of transverse momenta $\geq 10\text{--}12$ GeV/ c . Recall that we have adjusted the parameter for energy loss per collision, κ , for each centrality. The linear increase of variation of dE/dx with the average path length $\langle L \rangle$ for the Pb-Pb collisions at 2.76 ATeV is an interesting confirmation of similar findings for the Au+Au and Cu+Cu collisions at top RHIC energy in Ref. [2] (see Fig. 4). We also note that the dE/dx rises more rapidly with $\langle L \rangle$ as the energy increases. It remains to be seen if it rises even more steeply at the top LHC energy at which experimental results are eagerly awaited.

The magnitude of energy loss for a given path-length increases by a factor of 2–3 as we go from RHIC (200 AGeV) to LHC (2.76 ATeV). Thus we reconfirm the prediction of Baier *et. al.* that the total energy loss of the parton, ΔE is proportional to L^2 at 2.76 ATeV, as well.

We can estimate the average momentum transport coefficient \hat{q} using Eq. 6 for the QGP medium. We find that \hat{q} varies from 0.63 GeV 2 /fm for 0–5% centrality to 0.91 GeV 2 /fm for 30–50% centrality of collisions of Pb nuclei at 2.76 ATeV. This is about 2.5 times higher than the same obtained for Au-Au collisions at 200 AGeV, using a similar analysis [2]. The smaller value of \hat{q} at more central collisions may look surprising at first. However the width of the transverse momentum distribution of the parton, $\langle p_{Tw}^2 \rangle = \hat{q}\langle L \rangle$ [9], can be found to be 3.36 GeV 2 for 0–5% centrality and 2.70 GeV 2 for the 30–50% centrality.

We have also calculated the azimuthal anisotropy of the transverse momentum distribution of hadrons for $p_T \geq 10$ GeV/ c for non-central collisions as before in Ref. [2]

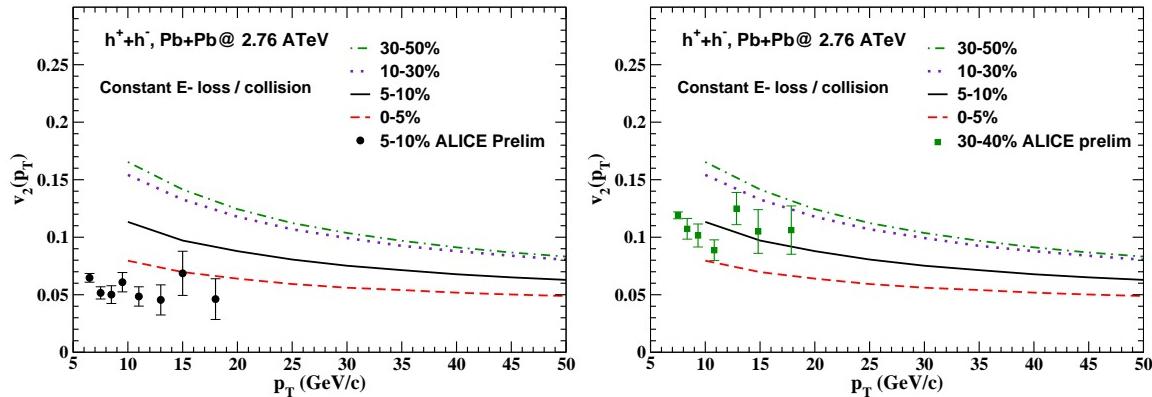


Figure 5. (Color online) The differential azimuthal anisotropy coefficient, $v_2(p_T)$ for the transverse momentum of hadrons for different centralities, using the parameter obtained earlier for Pb+Pb collisions at LHC at 2.76 ATeV. The experimental data are from the ALICE Collaboration [15].

and a typical result is shown in Fig. 5. We note that our results are larger by a factor of about 2 for the most central collisions and about 1.5 for less central collisions, when compared to the data from the ALICE Collaboration [15]. This can perhaps be attributed to uniform density of nuclei and a static medium assumed here.

In brief, we have analyzed the centrality dependence of nuclear modification of hadron production in collision of lead nuclei at 2.76 ATeV, due to jet quenching. NLO pQCD is used to generate the distribution of partons which then lose energy by multiple scattering and radiation of gluons. The formation time of the gluons is used to formulate the effects of coherence, which is reflected in different forms of the energy loss per collision. The treatment giving an energy loss per unit length as proportional to the path length provides a very good description of the data for $p_T \geq 10$ GeV/c and leads to a momentum transport coefficient of about 0.6–0.9 GeV²/fm. A comparison with a similar analysis for collision of gold nuclei at 200 AGeV can be used to suggest a more rapid rise of dE/dx with path length and an increased energy loss per collision at the top LHC energy.

Deviation from this expectation will mean a saturation of energy loss of partons as the temperature of the medium rises and confirmation will mean that it may or may not appear at higher temperatures. In either case, the awaited results will be of great interest.

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